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Contribution of climate and land cover changes to reduction in soil erosion rates within small cultivated catchments in the eastern part of the Russian Plain during the last 60 years

Artem V. Gusarov[a], Valentin N. Golosov[b,*], Aidar G. Sharifullin[a]

[a] Institute of Environmental Sciences, Kazan Federal University, 18 Kremlyovskaya Street, Kazan 420008, Russia
[b] Faculty of Geography, Lomonosov Moscow State University, Leninskiye Gory, 1, Moscow 119991, Russia

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ABSTRACT

The eastern part of the Russian Plain is an important agricultural region of European Russia with high proportion of cultivated lands in the steppe, forest-steppe and forest (southern part) landscape zones. Soil erosion is the main process of land degradation and surface water contamination there. Climate and land cover changes have been observed in this region during the last 30 years. However, field quantitative assessments of soil erosion rates are not available for the eastern part of European Russia due to the lack of monitoring data as well as the evaluation of erosion/deposition processes in cultivated catchments using other field methods. Three representative small cultivated catchments with high (> 80%) proportion of cultivated lands were selected in the forest (southern part), forest-steppe and steppe zones of the study region to evaluate sedimentation rates in dry valley bottoms of the catchments for two-time intervals (1963–1986 and 1987–2016) based on the application of the bomb-derived and Chernobyl-derived ^{137}Cs isotope for sediment dating. The 3–4 depth ^{137}Cs profiles were used to assess the sedimentation rates within the each investigated catchment. It was established that the sedimentation rates have considerably decreased (at least 2–3 times) over the last 30 years compared to 1963–1986 in all the investigated catchments. This is in agreement with results of erosion rate calculations using erosion models for the forest zone, however not consistent with erosion rates assessments for the forest-steppe and steppe zones. According to the model calculations, erosion rates show a slight decrease in the forest-steppe zone and increase in the steppe zone. The reduction in surface runoff during snowmelt period is one of the reasons for decrease in erosion rates within cultivated slopes for all the investigated catchments. The increase in proportion of perennial grasses in the regional crop rotation is another important reason for the decrease in erosion rates for the catchment located in the south of the forest zone. The importance of land cover changes in a major decrease of soil losses from the cultivated fields of the investigated catchments located in the forest-steppe and steppe zones cannot be identified due to the lack detailed information about crop rotation for those particular sites. However, available regional information about crop rotation changes for the two-time intervals (1960–1980 and 1996–2012) do not explain very high reduction in sedimentation rates in the dry valley bottoms after 1986.

1. Introduction

It is well-known that soil degradation is one of the main threats to sustainable development of agriculture. Soil erosion is one of the main process responsible for land degradation, leading to high financial losses due to reduction of soil productivity (Pimentel, 1993; Uri and Lewis, 1998; Podmanicky et al., 2011), for lateral migration of mineral fertilizers, pesticides, heavy metals and other substances transported with sediments, eventually leading to contamination of soils located in different sediment sinks along pathways from cultivated slopes to river channels (Mullan and Favis-Mortlock, 2011), surface water pollution (Collins et al., 2012), siltation of ponds and reservoirs (Boardman et al., 2009) and eutrophication of terrestrial waterbodies (Morgan, 2009) and so on. Attempts to estimate the intensity of erosion rates under the global (and regional) climate change (Favis-Mortlock and Mullan, 2011; Mullan, 2013; Routschek et al., 2014) and land use changes (Govers et al., 2006; Cebecauer and Hofierka, 2008; Latocha et al., 2016; Golosov et al., 2017a; Vanwalleghem et al., 2017) were made for the different parts of Europe using a combination of erosion models and GIS analysis. The application of various tracers (fallout radionuclides,

* Corresponding author.
E-mail address: gollossov@rambler.ru (V.N. Golosov).

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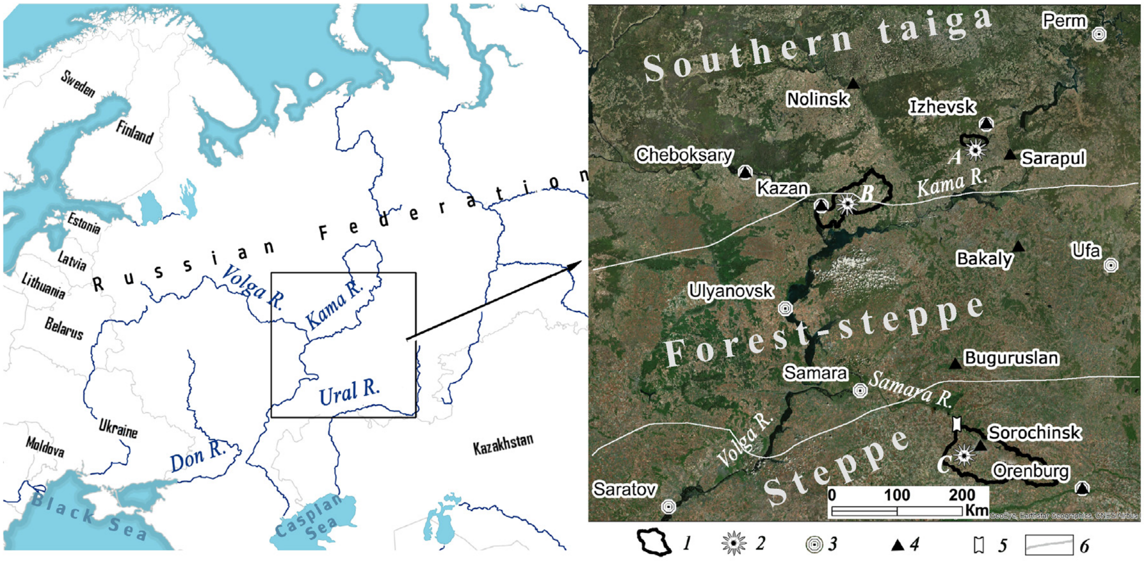

Fig. 1. Location of the investigated small catchments in the eastern part of the Russian (East European) Plain. *1* – the boundaries of the river basins which includes the catchments; *2* – the small catchments (*A* – Kuregovo, *B* – Temeva Rechka, *C* – Pogromka); *3* – the regional centers (cities); *4* – the weather stations; *5* – the Samara River hydrological gauging station at the village of Yelshanka (Orenburg Oblast, Russia); *6* – the boundaries of the landscape zones of the Russian Plain (according to National Atlas of Soils of the Russian Federation, 2011).

spherical magnetic particles etc.) also allowed to estimate recent trends in erosion rates in small catchments (Zapata, 2002; Mabit et al., 2008; Olson et al., 2008; Belyaev et al., 2009; Gennadiev et al., 2010; Porto et al., 2011, 2014; Golosov et al., 2011, 2017b; Gusarov et al., 2018, and others). Also, the dynamics of erosion processes within river basins is evaluated based on the analysis of the monitoring data on water discharges and sediment yield of regional rivers (Gusarov, 2001; Walling and Fang, 2003; Dedkov and Gusarov, 2006; Syvitski and Kettner, 2011; Vanmaercke et al., 2012, and others). In other studies, practical issues were considered to the analysis of the soil erosion effect on agricultural land productivity under the recent climate and land use changes (Bakker et al., 2008; Foucher et al., 2014, and others), sediment-associated pollutants lateral migration and their influence on the environment (Ayrault et al., 2014; Desmet et al., 2012, and others). Both rainfall erosion during the warm period of year (since the second half of April till October) and erosion during snowmelt (March and the first half of April) are observed in European territory of Russia (ETR), where the last decades are characterized by significant climate and land use changes (Shmakin and Popova, 2006; Adam et al., 2009; Choi et al., 2010; Popova and Polyakova, 2013; Madsen, 2014; and others). The climate change has contributed to an increase in air temperature in the winter months, and, as a consequence, a decrease in the depth of freezing of regional soils (Park et al., 2014). As a result, the surface runoff from the cultivated slopes during spring snowmelt decreased in the different landscape zones of European Russia from 23 to 49 mm in 1959–1981 up to 1–9 mm during the last 2–3 decades according to the monitoring observations on the runoff plots (Barabanov et al., 2018). It coincides with change of the intra-annual water flow redistribution in favor of decreasing of proportion of spring flood in the river flow with a simultaneous growth of lower water flow during summer time (Frolova et al., 2015). According to the erosion model, calculations undertaken for the entire ETR, the annual erosion rates have reduced in the forest and forest-steppe landscape zones during the period 1991–2015 as compared to the period 1960–1980 by 1.3–1.8 times: from 7.3 and 4.3 Mg ha^{-1} yr^{-1} to 4.1 and 3.3 Mg ha^{-1} yr^{-1}, respectively (Golosov et al., 2017a). At the same time, the erosion rates in the steppe zone, on the contrary, have increased by 1.2 times, from 3.9 to 4.6 Mg ha^{-1} yr^{-1}. Unfortunately, there are no available results of field investigations of erosion rates during the last 30 years for the eastern part of the ETR. So, it is not possible to verify the results of the erosion model calculations. The national soil erosion surveys carried out in all regions on a regular basis until 1991, are no longer undertaken since the USSR collapse. One of the possibility to identify a trend in the mean soil erosion rates for the two-time intervals is to define sedimentation rates on dry valley bottoms of first-order agricultural catchments using the bomb-derived and Chernobyl-derived ^{137}Cs fallouts for sediment dating (Golosov et al., 2006; 2017b). The sedimentation rates in sediment sinks located nearby from cultivated fields are directly proportional to intensity of sheet, rill and gully erosion in the catchment area. This approach can be used to identify a trend in soil erosion rate changes on croplands (Porto et al., 2016; Golosov et al., 2017b). Nevertheless, methodologically it is still difficult to evaluate the erosion rates on the slopes only using data on the dynamics of sedimentation rates, unless a catchment is not a closed system (lake, reservoir, pond, etc.) intercepting almost all the sediments.

The objective of this study are to define a trend of the changes in soil erosion rate for the two-time intervals (1963–1986 and 1986–2015) within the most agriculturally developed regions of the eastern part of the ETR based on detailed evaluation of sedimentation rates in the valley bottoms of selected first-order small agricultural catchments located in the forest, forest-steppe and steppe zones of this region, and to evaluate the contribution of climate and land cover changes to the revealed changes in soil losses.

2. Material and methods

2.1. Study area

Three small catchments located in different landscape zones in the eastern part of the ETR (the east part of the Volga River basin) were selected for detail investigation (Fig. 1) based on the following principles. Firstly, the area of cultivated lands on the catchments should exceed 80% and has not been considerably changed since the mid-1950s. Secondly, the relief of the catchments should be similar to the region type of relief. All the regions of the ETR investigated were affected by global warming with an increase in winter air temperatures according to meteorological observation data (Table 1). The lithology of the catchments is deluvium/solifluction loams of the Late Quaternary, lying on the multifarious complex of marine and terrigenous deposits of the Late Paleozoic and Early Mesozoic of the sedimentary cover of the

Table 1
Some climate characteristics of the study areas of the Russian Plain for two-time intervals, based on the data of the nearby weather stations (see Fig. 1).

Characteristics	Time intervals	Cities (weather stations) / small catchments		
		Izhevsk / Kuregovo	Kazan / Temeva Rechka	Sorochinsk / Pogromka
Mean annual temperature, °C	1946–1986	2.3 ± 0.3[a]	3.4 ± 0.3[b]	4.2 ± 0.3
	1987–2015	3.2 ± 0.3	4.9 ± 0.6	5.3 ± 0.4
Mean temperature for three calendar winter months, °C	1946–1986	–12.8 ± 0.9	–11.6 ± 0.9	–12.3 ± 0.9
	1987–2015	–11.6 ± 0.8	–9.7 ± 0.8	–10.8 ± 0.9
Mean temperature for March, °C	1946–1986	–6.5 ± 0.8	–6.2 ± 0.8	–6.6 ± 0.9
	1987–2015	–4.8 ± 0.8	–3.6 ± 0.8	–4.7 ± 1.1
Precipitation for cold period (November–March), mm	1960–1985	174 ± 28	159 ± 14	111 ± 14
	1986–2015	152 ± 14	210 ± 20	141 ± 14
Precipitation for warm period (April–October), mm	1960–1985	353 ± 32	370 ± 32	233 ± 18
	1986–2015	366 ± 27	356 ± 28	255 ± 23
Mean water storage in snow for last 10 days of March, mm	1966–1985	144	106	39
	1986–2015	173	148	53
Total number of rain events with rainfall depth > 20 mm, un. /10 years	1966–1985	7.0	15.0	3.5
	1986–2015	11.0	12.7	9.0

[a] For 1958–1986.
[b] For 1950–1986.

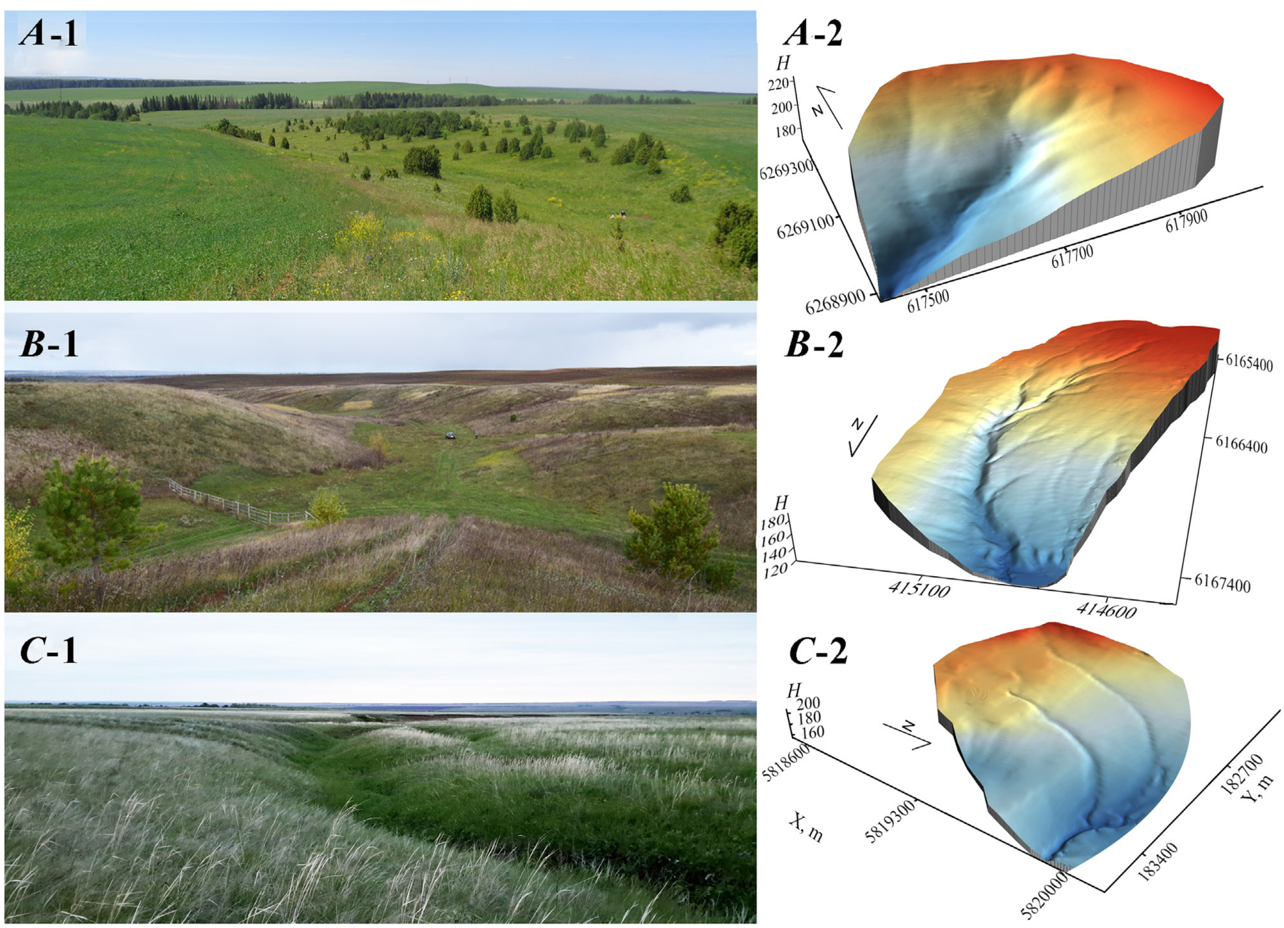

Fig. 2. The investigated small catchments (1 – photos of the main dry valleys of the catchments, 2 – the digital elevation models of the catchments). *A*-1 and *A*-2 – the Kuregovo catchment, *B*-1 and *B*-2 – the Temeva Rechka catchment, *C*-1 and *C*-2 – the Pogromka catchment; *H* – height, m a.s.l.; X/Y – geographic coordinate system.

Russian tectonic platform. General views of the catchments and their dry valleys are presented in Fig. 2. Some morphometric and landscape characteristics of the investigated catchments are shown in Table 2. The main difference between the catchments is a hollow density within their cultivated slopes which significantly influences the proportional input of the ephemeral gully erosion and sheet and rill erosion, as well as the sediment delivery from the slopes to the dry valley bottoms. The Temeva Rechka catchment is characterized by a most dense network of the hollows (see Table 2). The Pogromka catchment has two large hollows with the lengths of 1890 m (western) and 1310 m (eastern). In the Kuregovo catchment such hollows are shallow and sporadic (see Fig. 2). It is also important to note that soils with different resistance to erosion are distributed within different catchments.

Table 2
Some morphometric and landscape characteristics of the investigated small catchments of the eastern part of the Russian Plain.

Characteristics	Small catchments		
	Kuregovo	Temeva Rechka	Pogromka
Morphometric characteristics			
Catchment area, km^2	0.68	1.13	1.92
Mean height, m a.s.l.	167	161	176
Altitude amplitude, m	76	74	45
Average slope of the catchment surface, °	3.3	2.9	2.0
Dry valley length (together with main hollow), m	400 (680)	1635 (2087)	247 (2137)
Dry valley density, km km^{-2}	0.59	1.45	0.13
Hollow density, km km^{-2}	1.25	2.70	1.67
Landscape characteristics			
Landscape zone (subzone) of the temperate climate belt	Southern taiga	Northern forest-steppe	Southern steppe
Predominant soils (according to WRB, 2014)	Sod-podzolic soils (*Umbric Albeluvisols Abruptic*)	Gray forest soils (*Greyic Phaeozems Albic*)	Southern Chernozems (*Haplic Chernozems Pachic*)
Cultivated area, %	92	87	83

2.2. Methodological approach

All the investigated catchments were affected by both bomb-derived and Chernobyl-derived ^{137}Cs fallouts. The caesium-137 is the man-made isotope which was being released in the environment from the beginning of nuclear bomb testing in 1954 until 1980 with the maximum fallout in 1963; and the second peak in the radionuclide global fallout was in 1959 (Fig. 3). Later, the Chernobyl-derived ^{137}Cs fallout associated with the accident at the Chernobyl nuclear power plant was observed in April–May 1986 in the different parts of Europe, including the entire ETR. The vertical migration of ^{137}Cs peak concentration for most soil types was found to occur within 2–3 cm (Owens et al., 1996; Zapata, 2002; Buraeva et al., 2015). Therefore, most active vertical migration of the ^{137}Cs occurred in the first years after its fallout from the atmosphere (Smith and Elder, 1999). The ^{137}Cs peaks with high accuracy (± 2–3 cm) indicate a soil (stratozem, Fluvisols, according to WRB, 2014) surface of the first-order dry valley bottoms and other sediment sinks for the years with maximum ^{137}Cs fallout within the ETR (1959, 1963 and 1986). If sediment layers deposited over the last 60 years were not disturbed by secondary gully (rill) bottom incision, it is possible to identify each ^{137}Cs peaks and to determine sedimentation rates over three-time intervals – 1959–1963, 1963–1986 and since 1986 up to the time of sampling. However, it is difficult to identify ^{137}Cs peak of 1959 in most cases due to lower ^{137}Cs concentration in the soil of the Russian Plain, as compared to the ^{137}Cs peak of 1963 (see Fig. 3), and also because it is now almost two half-lives of ^{137}Cs since the fallout occurrence.

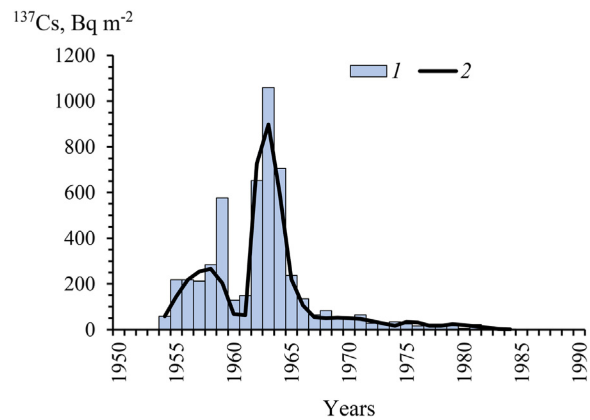

Fig. 3. The annual (bomb-derived ^{137}Cs fallouts (*1*) in the Northern hemisphere (according to the generalized data of Zapata, 2002) and (*2*) in the Leningrad Oblast of the former Soviet Union (according to Silantyev and Shkuratova, 1983) during 1954–1984.

2.3. Field studies

High-resolution aerial survey was carried out at each catchment under study using unmanned aerial vehicle DJI Phantom 4 which allowed constructing a digital elevation model (DEM)[1] of the catchments (see Fig. 2). Different landscape elements influencing sediment redistribution were identified based on field survey and DEM analysis including boundaries of the cultivated fields, bottom gullies, old rills overgrown with vegetation on the uncultivated valley banks, as well as different morphological and land-use elements of the catchment slopes (hollows, ground roads, levees and so on). As a result, the main runoff and sediment pathways from the cultivated slopes to the valley bottoms were identified. The detailed field geomorphic mapping was undertaken within the uncultivated parts of each catchment, allowing to select more precisely the boundaries of the main morphological elements (valley banks and bottoms, and bottoms of small erosion headcuts, sediment fans and so on) (Fig. 4). The geomorphic maps were used for selection of appropriate locations for sediment sampling within the dry valley bottoms as the main sediment sink. The 3–4 sampling points (see Fig. 4) were selected for depth incremental sampling along each valley bottom depending on its morphological features. A sediment section (incision) was excavated in each sampling point, and a detailed description of the soil profile morphology was done. Then the profile face with the minimum disturbance by bioturbation was selected for depth incremental sampling. Sediment samples for radionuclide analysis were collected from an area 15 × 15 cm at 2–3 cm depth increments for the upper 60–70 cm and at 5 cm depth increments below 60–70 cm. In the latter case, the sampling area was reduced to 10 × 10 cm. Samples for the grain size analysis were taken only on the dry valley bottom of the Pogromka catchment. Both other catchments are characterized by the predominance of the silty fraction, both within their arable lands and in dry valley bottoms.

2.4. Laboratory analyzes

Subsequent laboratory processing of the ^{137}Cs samples involved oven-drying at 105 °C, grinding, sieving to < 2000 μm and homogenization of sub-samples for γ-analysis. Plastic pots were used for analyzing the 100–110 g sub-samples obtained from the depth of incremental samples. The ^{137}Cs activity was measured at 661.66 keV

[1] The resolution of the raw digital elevation models was 0.05 m, later they were smoothed out and resulted in 1 m resolution. This resolution allows analysis of such forms of relief as ephemeral gullies and hollows, with a lower size of the final DEM.

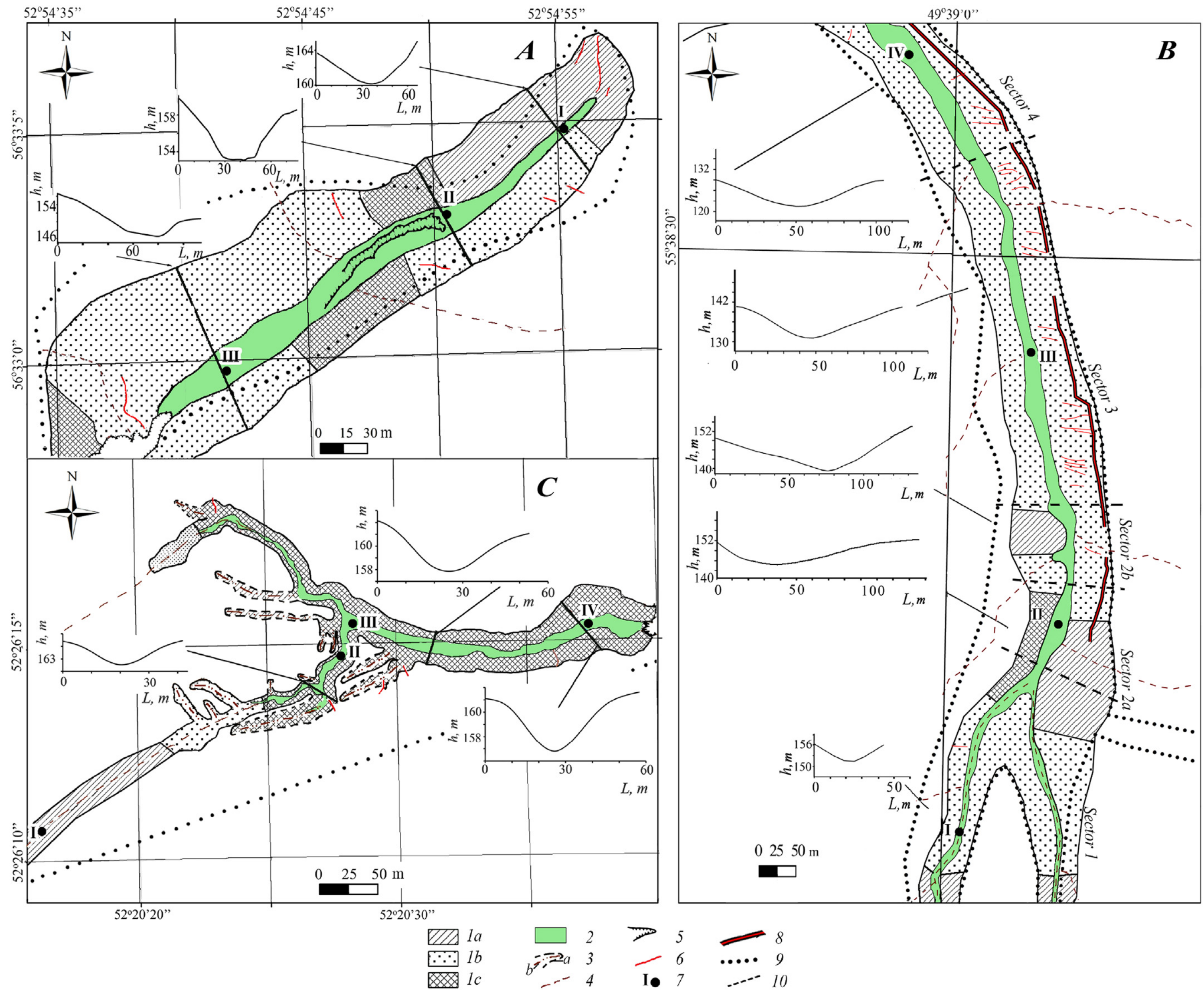

Fig. 4. Geomorphic maps of the investigated small catchment dry valleys (*A* – the Kuregovo catchment, *B* – the Temeva Rechka catchment, *C* – the Pogromka catchment). *1* – valley banks with different slopes: *1a* – 4–8°, *1b* – 8–15°; *1c* – > 15°; *2* – valley bottoms; *3* – slope gullies: *a* – break line, *b* – thalwegs; *4* – hollow thalwegs; *5* – bottom gullies; *6* – inactive valley bank rills; *7* – sediment sections and their numbers; *8* – levees with relative height app. 0.4–0.5 m (old boundaries of cultivated fields); *9* – modern boundaries of cultivated fields; *10* – boundaries of the morphodynamical sectors within the Temeva Rechka catchment dry valley; *dry valley cross-section profiles*: *L* – horizontal traversing, m; *h* – height, m a.s.l.

using a high-resolution, low-background, hyperpure germanium coaxial γ-ray detector with a maximum relative error of the isotope activity determination of ± 5–7%. Sample preparation, treatment and ^{137}Cs activity measurements were carried out at the Laboratory of Soil Erosion and Fluvial Processes, Faculty of Geography, Lomonosov Moscow State University (Russia).

The grain size analysis of the selected samples (less than 2000 μm in diameter) was done using laser diffraction of the Microtrac Bluewave S3500 analyzer (the three-laser technology) in the analytical laboratory of Kazan Federal University (Russia).

2.5. Evaluation of sedimentation rates based on ^{137}Cs dating

Based on the laboratory analysis results, the ^{137}Cs vertical distribution profiles were constructed for all the sediment sections for each investigated catchment bottom. Additionally, the volumes of sediments deposited in the valley bottoms over two-time intervals (1963–1986 and 1986–2016) were calculated for the Temeva Rechka catchment. The volume of accumulated sediment materials was determined by multiplying the dry valley bottom areas, to appropriate depth of the bomb-derived and Chernobyl-derived ^{137}Cs peaks taking into account the cross-section profile of the dry valley in the sampling location. The obtained volumes were translated to weight values by multiplying them by average density of the sediment samples.

2.6. Other data collection and interpretation

The Landsat satellite images of the investigated catchments for 1976–2016 were collected for evaluation of possible changes in the cultivated land area. It was found that the cultivated areas have not changed significantly within the catchments during the last decades, including the period after the USSR collapse in 1991. However, it was not possible to collect information about the actual crop rotations for the cultivated fields for the period under consideration. Data on the set of crops sown on the catchments since 1991 was obtained through interaction with local farmers. Information about typical crop rotations

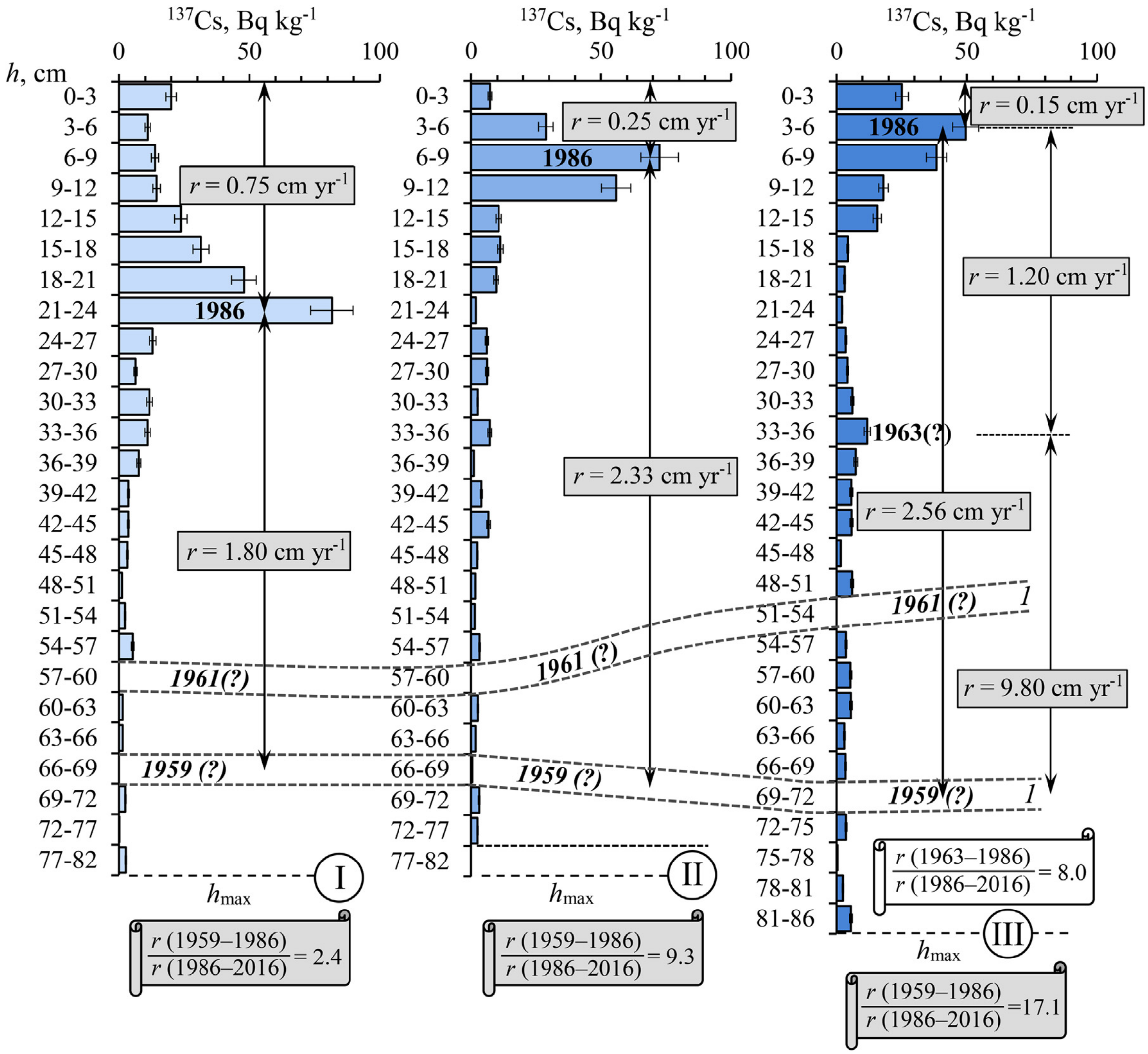

Fig. 5. Vertical distributions of ^{137}Cs concentration in the sediment sections I, II and III within the Kuregovo catchment dry valley bottom (see Fig. 4*A* for section locations). *h* – (h_{max} – maximum) depth of sampling; 1963/1986 – positions (for 1963 is assumed) of the dry valley bottom surface at the time of the peak ^{137}Cs isotope fallout of bomb-derived / Chernobyl origin; *r* – the average sedimentation rate for a corresponding period; *1* – the ^{137}Cs-free sediment strata accumulated as products of deep rill erosion on the dry valley banks (see Fig. 4) during some extreme runoff presumably in 1959 and 1961.

for the studied geographical region of the ETR during the USSR period (until 1991) was collected from the annual governmental reports about crop rotations for different administrative regions of the Russian Federation (Rosstat, 2015).

The meteorological data for 1950–2015 were collected from weather stations located nearby the investigated catchments in the cities of Izhevsk, Kazan, Nolinsk, Sarapul, Cheboksary, Bakaly, Sorochinsk and Buguruslan (see Fig. 1 for their locations). These data were available from the All-Russian Research Institute of Hydrometeorological Information – World Data Center, ARRIHI–WDC (http://meteo.ru). In addition, information about water and sediment discharges was collected for the upper reach of the Samara River (the left-bank tributary of the Volga River) for 1933/1940–2013.

3. Results

3.1. ^{137}Cs depth profile interpretation

The Chernobyl-derived ^{137}Cs peak (1986) is sufficiently well-defined in the ^{137}Cs vertical profiles of all the dry valley bottoms studied (Figs. 5, 7 and 8). It means that the sedimentation rates for the period between 1986 and the sampling dates can be evaluated with relatively high accuracy, but the accurate dating of the sediments deposited before 1986 is somewhat more complicated. The bomb-derived ^{137}Cs peak (1963) can be clearly identified in some ^{137}Cs vertical profiles. Taking into consideration a possible vertical ^{137}Cs migration due to bioturbation and other processes (including lateral ^{137}Cs migration from the catchment slopes), the entire thickness of the sediments containing the radioisotope below the Chernobyl-derived ^{137}Cs peak (1986) can be attributed to the period 1954–1986, since other sources of the artificial ^{137}Cs in the sediments (Fluvisols of the bottoms) during this period, except the nuclear bomb tests after 1954, were absent. However, it is impossible to establish exactly an initial level of the ^{137}Cs-fallout in 1954 due to three main reasons. Firstly, initial ^{137}Cs fallout of 1954 in subsequent fallouts associated with nuclear bomb testing in the open atmosphere for the period 1954–1980 (depositions) was very small. Secondly, taking into account the ^{137}Cs half-life (30.2 years) and time passed since its deposition (> 60 years), the current ^{137}Cs concentration in the sediments dated by 1954 is also extremely small. Thirdly, downward migration due to diffusion and bioturbation is greatly affected the "tail" of ^{137}Cs vertical distribution in sediment (Arapis et al., 1997).

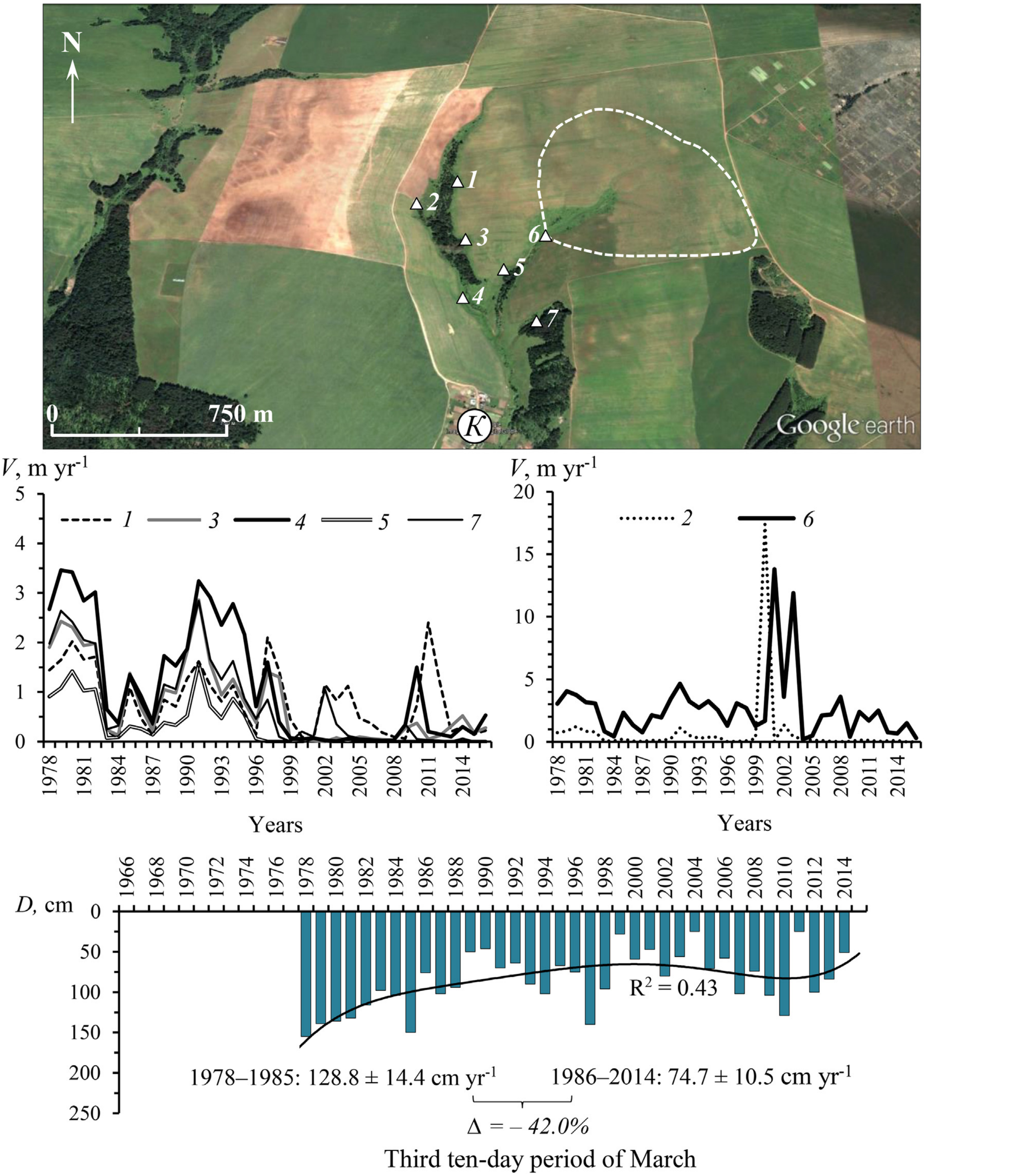

Fig. 6. Long-term changes in head retreats (*V*) of the gullies located nearby the Kuregovo catchment, and depth of frozen sud-podzolic soil (*D*, according to the data of the weather station in the city of Izhevsk, see Fig. 1 for location) during 1978–2015/2016. *K* – the village of Kuregovo (Udmurt Republic, Russia), Δ – relative difference between average *D*-values; R^2 – approximation coefficient of five-degree polynomial trend. *Note.* The gully heads are depicted in the Google Earth image as white triangles with their sequence numbers (*1*, *2* … *7*).

3.2. The Kuregovo catchment (south of the forest zone)

The detailed analysis of the vertical ^{137}Cs profiles at the bottom sediments within the dry valley of the Kuregovo catchment allows to reconstruct the history of changes in the erosion/sedimentation rates in the catchment area over the last 60 years (see Fig. 5). It is possible to suggest based on ^{137}Cs vertical profile interpretation, that the maximum rates of slope erosion were observed at the turn of the 1950s–1960s. The rates of eroded soil sedimentation in the dry valley bottom were about 1.8–2.6 cm yr^{-1} for 1959–1986, while for the period 1986–2016 – only 0.15–0.75 cm yr^{-1}, i.e. it decreased by at least app. 2.5 times (see Fig. 5). The sedimentation rates were increasing along the dry valley bottom from the upper reach (sediment section I, 1.8 cm yr^{-1}) to the lower one (sediment section III, 2.6 cm yr^{-1}) during 1959–1986. While after 1986 the situation was inverted: more intensive deposition was observed in the upper reach (sediment section I,

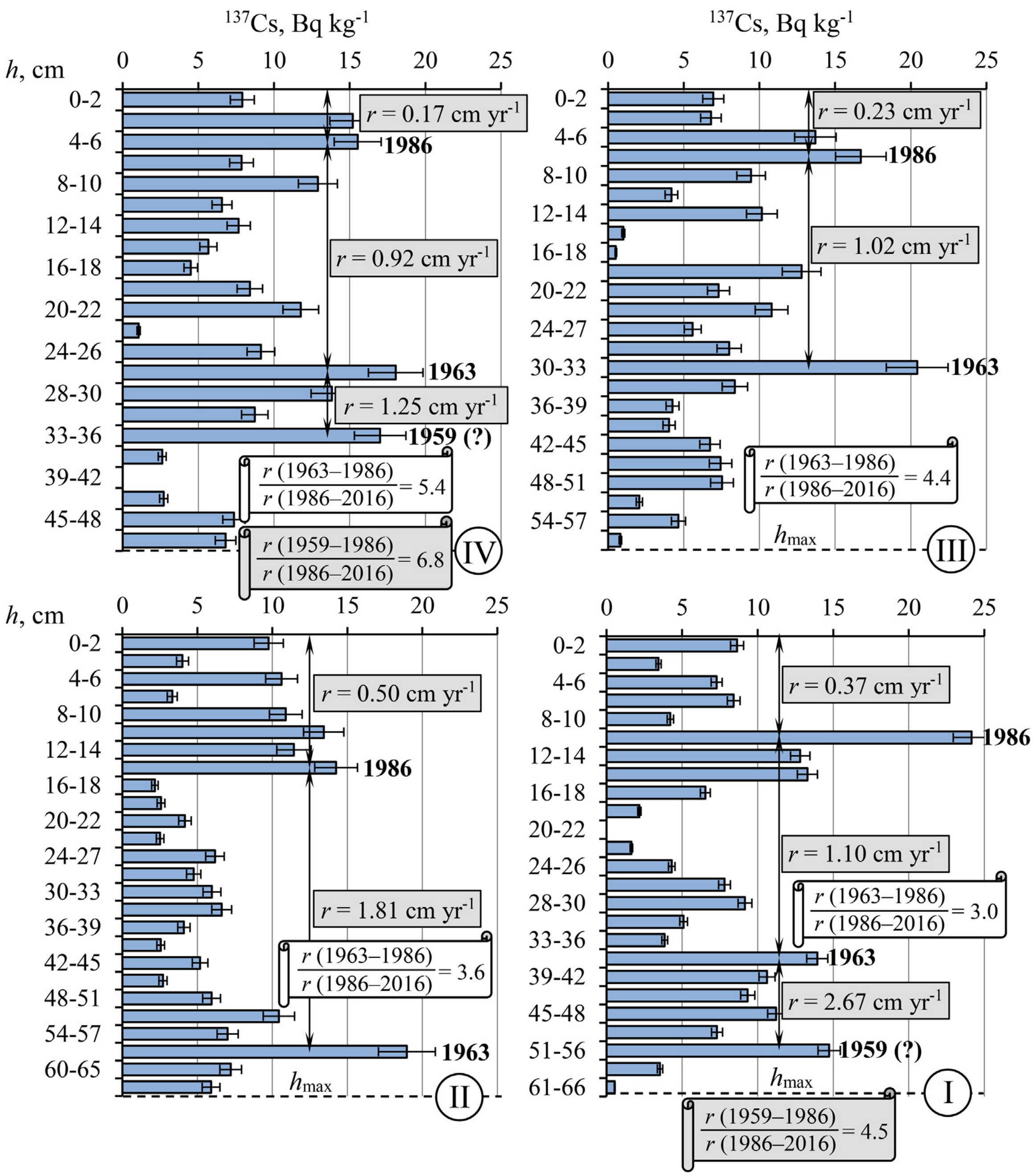

Fig. 7. Vertical distributions of ^{137}Cs concentration in the sediment sections I, II, III and IV within the Temeva Rechka catchment dry valley bottom (see Fig. 4*B*). Other symbols see Fig. 5.

0.75 cm yr^{-1}) and the lowest sedimentation rate was for lower (sediment section III, 0.15 cm yr^{-1}) sectors (see Fig. 5). The mentioned tendencies clearly indicate a principal change in the conditions of surface runoff and erosion within the catchment area after 1986. It is more likely that high surface runoff was formed on the cultivated slope during the spring snowmelt during 1960–80th with a relatively low sediment concentration. This is a typical situation for erosion during snowmelt (Golosov, 2006; Golosov et al., 2011). Since the beginning of 1990th the surface runoff during snowmelt reduced considerably. The reduction of surface runoff from the cultivated slope within the investigated area is confirmed by the results of long-term observation for gully headcut retreat during the last decades (Fig. 6). The observed trend of frozen soil depth reduction is consistent with decreasing of gully headcut retreat, allowing to suggest that reduction of surface runoff during snowmelt is directly depending on the depth of frozen soil. Some extreme rates of the headcut retreat of gullies located at the bottoms of dry valleys and hollows (the gullies no. 2 and 6 (see Fig. 6) are most likely related to the morphological features of these bottoms (the presence of tunnel erosion associated with a subsurface runoff).

The presence of some layers not containing ^{137}Cs in the sediment dated to 1954–1986 (see Fig. 5) may indicate that their formation was associated with high surface runoff from the catchment area which led to intensive rill, ephemeral and bottom gully erosion. ^{137}Cs concentration in the soil horizons deeper 25 cm is close to zero (Zapata, 2002). Such deep incisions have been widely presented on the dry valley banks (old rill cuts) and in the middle reach of the dry valley bottom (bottom gullies) (see Fig. 4A). At the present time they are completely covered by perennial grass vegetation. These erosion cuts were formed in the period until 1963, because they are located in the sediment section III deeper than the bomb-derived peak of ^{137}Cs. It is

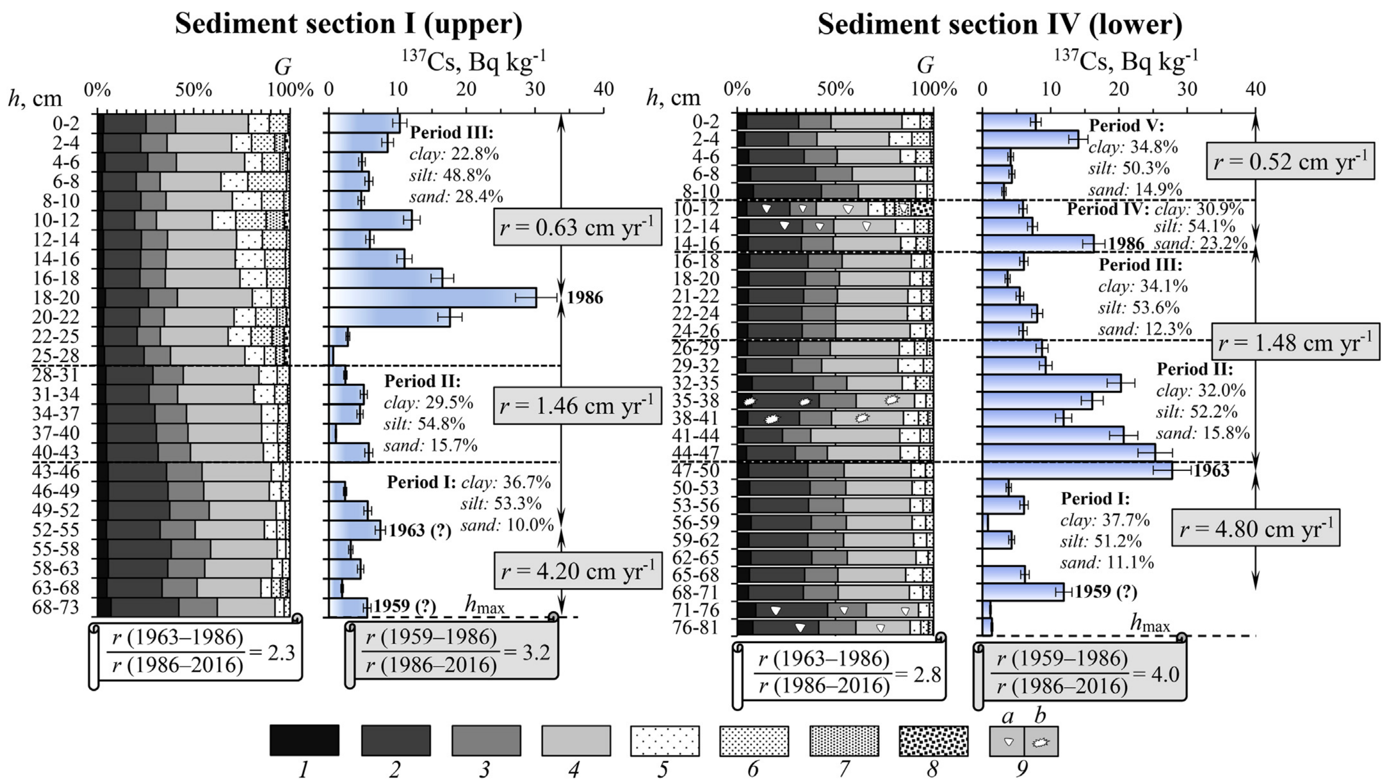

Fig. 8. Vertical distributions of ^{137}Cs concentration and sediment texture (*G*) in the sediment sections I and IV within the Pogromka catchment dry valley bottom and its right-side hollow-tributary (see Fig. 4*C*). The sediment texture (according to Yapaskurt, 2008): *clay: 1* – fine-grained (0.2–1 µm), 2 – coarse-grained (1–5 µm); *silt: 3* – fine-grained (5–10 µm), *4* – coarse-grained (10–50 µm); *sand*: *5* – ultrafine-grained (50–100 µm), *6* – fine-grained (100–250 µm), *7* – medium-grained (250–500 µm), *8* – coarse-grained + ultracoarse-grained (500–2000 µm); *9* – carbonates (*a* – differently-rounded marl breakstone, *b* – carbonate concentrations (neoformations)). Other symbols see Fig. 5.

more likely that extreme erosion events were observed in the study area twice in 1959 and 1961. In particular, high erosion could be observed after the snowy winter season 1960/1961: the monthly precipitation abnormally high for this region (90 mm) was recorded in April 1961 during and immediately after snowmelt and before the sowing period which is usually in second half of May in the southern part of the forest zone of the ETR. During this abnormal month the local sud-podzolic soils were already thawed, but still poorly protected by crops and grass vegetation. It is also important to note that the total precipitation during the warm seasons of 1959 and 1961 were 390.9 and 391.4 mm, respectively, that is above the mean annual values for 1960–1985 (Table 1).

3.3. The Temeva Rechka catchment (north of the forest-steppe zone)

The ^{137}Cs peaks dated by 1963 and 1986 are clearly identified in all the sediment sections of the Temeva Rechka dry valley bottom (Fig. 7). The ^{137}Cs peak of 1959 is also distinguished in two sections. The sedimentation rates in the dry valley bottom of the Temeva Rechka catchment during 1963–1986 are estimated at 0.92–1.81 cm yr^{-1}, whereas during 1987–2016 they were 0.17–0.50 cm yr^{-1}, that corresponds to a decrease by 3.0–5.4 times. As was the case of the Kuregovo dry valley, a trend of sedimentation rate reduction was seen along the valley bottom from the upper reach to the lower one (see Fig. 7). In this case it can be explained by the morphological features of valley bottom – increasing the bottom width in the same direction (see Fig. 4B).

It is also possible to perform rough estimation of the total sediment deposition for the different reaches of the dry valley bottom based on sedimentation rates and morphological characteristics of the dry valley. The proportion of the total sediment deposition (on the unit of bottom area) between two-time intervals (1963–1986 and 1987–2016) also changed along the valley bottom. This proportion between 1963–1986 and 1987–2016 was about 2.5–3.0 in the two upper sectors (see Fig. 4B for their locations), while in the two lower sectors it was about 3.5–4.5. The high reduction in the sedimentation rates in sectors 3 and 4, located in the central and low reaches of the dry valley bottom, during 1987–2016, as compared to previous time interval (1963–1986) can be explained by the two main reasons: firstly, by reduction in erosion rates during snowmelt, and, secondly, by increase in sedimentation on the uncultivated bottom part of the right slope of the valley due to relocation the cultivated field boundary in the direction of watershed line by 10–15 m (see Fig. 4B).

3.4. The Pogromka catchment (south of the steppe zone)

In all the sediment sections in the dry valley bottom of this catchment, the Chernobyl-derived ^{37}Cs peak is buried by sediments deposited since 1986 at comparatively close depth of 0.14–0.20 m. Based on interpretation of ^{137}Cs depth distribution curves it is possible to assess the average sedimentation rates in 1.5 cm yr^{-1} and 0.52–0.68 cm yr^{-1} for 1963–1986 and 1986–2016 respectively (Fig. 8). The reduction in sedimentation rates by 2.3–2.8 fold during the last three decades was identified. The following analysis of the ^{137}Cs depth distribution curves allows to suggest, that the sedimentation rates until 1963 were probably even significantly higher (see Fig. 8). Against the background of the noted tendency, there is also a tendency of changes in grain size composition (texture) of the different-aged sediments. So, the uppermost sediment layers of the Section 1 (see Fig. 8), accumulating presumably after 1983–1984, has lowest content of clay fraction (including fine-grained clay fraction is about 3%) and high content of sand fraction. The sediment layer, which is approximately dated by 1959–1967, is the highest in the clay (including the fine-grained clay

fraction is about 6%) and smallest in the sand – almost three times smaller than in the upper thickness (see Fig. 8). It is likely that the given change in sediment grain size indicates the differences in slope runoff which occurred over the last decades. High proportion of clay particle is attributed to the period of prevalence of snowmelt runoff during 1960th with lower sediment concentration, whereas increasing of sand proportion is associated with high sediment concentration runoff due to ephemeral gully and rill erosion observed during extreme rain-storms. In addition, as within the other investigated catchments, the ratio of sedimentation rates between two-time intervals had a tendency to increase downstream (see Fig. 8).

4. Discussion

The reduction in sedimentation rates in the dry valley bottoms during 1986–2016 compared to 1963–1986 was identified for all the investigated catchments. It may be suggested that both climate change and possible changes in crop-rotations led to serious decreasing of soil losses from the catchment areas, and, as a consequence, to reduction in the sedimentation rates there.

4.1. Hydroclimatic changes

The tendency of increase in soil temperature, as well as reduction in frozen soil depth, is observed within the whole eastern part of the Russian Plain (Table 3). It is associated with increase in air temperature, mostly during winter time, since the end of 1970s (Park et al., 2014). It is the main reason of reduction in runoff coefficient during spring snowmelt from 0.3 to 0.5 in 1960–1970s up to 0.01–0.05 in 2000–2010s, according to the data of field monitoring for 1959–2016 on the experimental stations located in the western and central parts of the forest-steppe and steppe landscape zones of the Russian Plain (Barabanov et al., 2018). This significant reduction in the surface runoff from cultivated slopes during snowmelt is confirmed by the increase in water discharges during summer low water seasons in river basins with high proportion of cultivated lands located in the southern half of ETR (Frolova et al., 2015). A similar trend for decline of water discharges during spring floods in the last decades has also been found in the Baltic countries (Estonia, Latvia and Lithuania) (Sarauskiene et al., 2015), as well as in Eastern Scandinavia (Arheimer and Lindström, 2015), Poland, Belarus, and in the north of Ukraine (Kaczmarek, 2003). It has been noted that the surface runoff is not observed during snowmelt if the depth of frozen soils is lower than 30–38 cm, according to the observation (Komissarov and Gabbasova, 2014) on the arable lands of the Southern Cis-Ural located to the north-east from the Pogromka catchment. The considerable reduction in the surface runoff is expected to lead to decrease in soil erosion rates during snowmelt in different landscape zones of the southern half of the Russian Plain.

Table 3
The changes in mean temperature (°C) at the different soil depths for last 10 days of March (pre-snowmelt period) during two-time intervals of 1963–2011 according to the data of some weather stations in the study region of the Russian Plain (see Fig. 1).

Weather stations (cities, towns)	Time intervals	Soil depths		
		160 cm	80 cm	20 cm
Cheboksary	1963–1986	1.70 (0)[a]	0.40 (20)	−0.41 (100)
	1987–2011	2.00 (0)	0.47 (20)	−0.28 (65)
Nolinsk	1963–1986	2.27 (0)	0.59 (6)	−0.39 (80)
	1987–2011	2.48 (0)	0.94 (4)	−0.02 (46)
Sarapul	1963–1986	1.82 (0)	0.38 (22)	−0.42 (78)
	1987–2011	2.51 (0)	1.06 (4)	0.00 (48)
Bakaly	1963–1986	1.31 (6)	−0.35 (52)	−0.90 (90)
	1987–2011	1.94 (0)	0.62 (15)	−0.30 (58)
Buguruslan	1963–1986	1.01 (17)	−0.49 (57)	−0.54 (79)
	1987–2013	1.64 (7)	0.09 (37)	0.27 (59)
Orenburg	1977–1986	1.94 (0)	0.04 (40)	– (–)
	1987–2011	2.98 (0)	1.10 (8)	0.19 (36)

[a] Hereafter, in parentheses is the portion (%) of years with a negative mean soil temperature at the given depth for the corresponding time interval.

Results of hydrological observation on the local rivers are also indicative of soil loss reduction within the investigated catchment during snowmelt since the mid-1980s. As an example, we present the results of monitoring data on the Samara River, in the basin of which the Pogromka catchment is located (see Fig. 1). The analysis of long-term changes in water flow and suspended sediment yield of the Samara River enables us to distinguish there at least three main hydrological periods: 1940–1967, 1968–1984 and 1985–2012 (Fig. 9). The average portion of snowmelt-induced flood flow from 1940–1967 to 1985–2010 decreased from 64% to 50% of annual flow value having a decrease in some years of the last period (1985–2010) even below 40%: 1989 – 36%, 1990 – 35%, 1992 – 32%, 1996 – 32%, 1997 – 29%, 2000 – 36%, in 2006 – 30%, and in 2009 – 33%. At the same time, in 1940–1967 this portion was below 50% only in: 1944 – 43%, 1961 – 47%, 1967 – 40%. Besides, the total layer (depth) of the snowmelt floodwater runoff in the entire Samara River basin (upstream the village of Yelshanka) decreased more than 20% between these periods, and the runoff intensity decreased by 36% against the background of increase in the duration of snowmelt flood by more than 20% (see Fig. 9). The decrease in flood flow during the snowmelt was accompanied by an increase in water discharges in the Samara River during the summer months (by 40% between 1940–1967 and 1985–2010, and during the autumn months (by more than 55%), including due to the increase in rainfall-induced floods (by 2.6 times) and their total duration (by 2 times) (Fig. 9). These changes in the intra-annual flow of the river, first of all, are indicative of a change in redistribution of surface and underground runoff in its basin during the spring season. Despite of the positive trend of mean annual water discharges since the mid-1980s, the high reduction of sediment yield is observed during the last three decades. Similar changes in hydrological regime during last three decades is observed also in the Myosha River and the Izh River basins, in which the Temeva Rechka and the Kuregovo catchments are located, respectively (Rysin et al., 2017; Safina, Golosov, 2018). Thus, in the Myosha River (at the village of Pestretsy, basin area is 3230 km^2) the following temporary dynamics of the maximum water discharges for the snowmelt-induced floods was noted: 1960–1975 – 589 ± 93 $m^3\ s^{-1}$, 1977–1988 – 394 ± 195 $m^3\ s^{-1}$, 1993–2000 – 73 ± 36 $m^3\ s^{-1}$. Also, according to the results of long-term monitoring the gully headcut retreat during spring snowmelt in the different parts of the Izh River basin, including the Kuregovo catchment, decreased by 4–5 times in 1998–2014 compared to 1978–1997 (see Fig. 6), mostly due to reduction in surface runoff from the cultivated slopes of the Udmurt Republic (Rysin et al., 2017).

A number of rainfalls with a rainfall depth more than 20 mm, their intensity and distribution during warm period of year (April–October) are the key indicators determining the soil erosion dynamics. Despite of the number of such rains is increased in each investigated area, except the Temeva Rechka catchment (Table 1), it is not influenced significantly on rainfall erosivity, because of the number of extreme rainfalls (> 40 mm) did not change considerably. However, particular extreme rainfalls contribute 70–80% of total soil losses according to the long-term monitoring data on the agricultural catchments (Edwards and Owens, 1991). For comparison, the number of erosion-hazardous rainfalls over the last 40 years on the plains of the Central Europe increased by 4–5% (Mueller and Pfister, 2011; Hanel et al., 2016). In this case it is necessary to take into account that the rainfall erosivity in the most parts of Europe is higher compared to the Russian Plain (Panagos et al., 2017a, 2017b). The USLE cropping coefficient for the warm season of year is at least 2–3 times higher than in the snowmelt period in the investigated area of the ETR (Litvin et al., 2017), and it can be assumed that the increase of summer rainfall did not promote

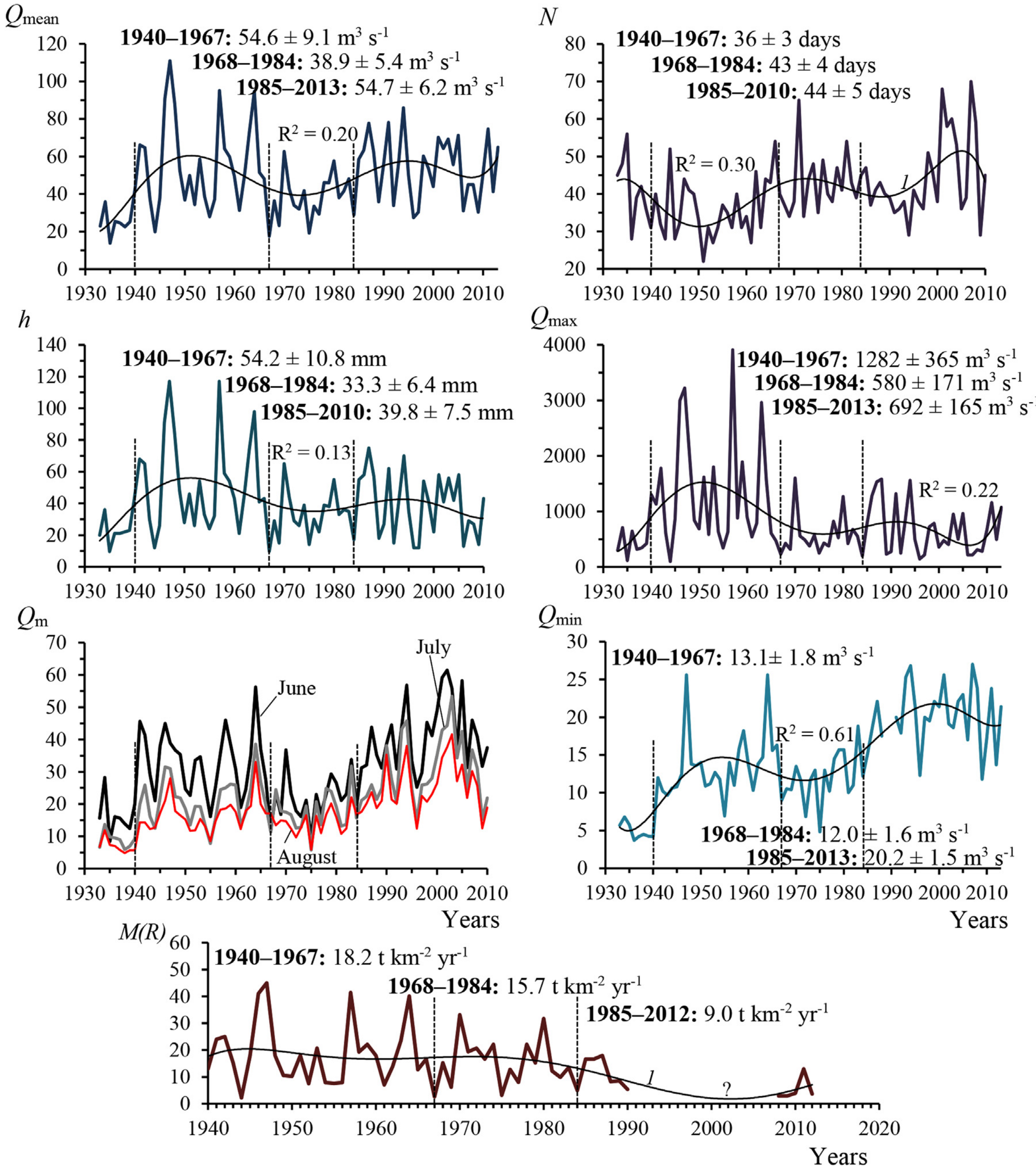

Fig. 9. Long-term changes in water flow and suspended sediment yield of the Samara River (basin area is 22,800 km²) nearby the village of Yelshanka, Orenburg Oblast of European Russia (see Fig. 1 for location), during 1936–2013. *Water discharges:* Q_{mean} – mean annual, Q_{max} – maximum annual (during the spring snowmelt period), Q_m – mean monthly for the summer months, Q_{min} – minimum one during the warm (river-ice-free) period; N – duration of the spring (snowmelt-induced) flood (days); h – total water flow layer in the basin during the spring (snowmelt-induced) flood (mm); $M(R)$ – specific suspended sediment yield (t km^{-2} yr^{-1}); R^2 – approximation coefficient of sixth-degree polynomial trend (*1*). *Note.* The separation of the three periods is based on analysis of the year-to-year Q_{mean} variability using the "changepoint detection", "changepoints analysis" methods performed using the PELT algorithm (Killick et al., 2012). The algorithm uses the likelihood ratio criterion first proposed by Hinkley (1970) for the purpose of detecting the change points in the average normally distributed observations. It is also based on minimizing a function that allows selecting segments of series that differ as much as possible from each other. The search for the change points was made using the "Changepoint" package (Killick and Eckley, 2014) in the statistical analysis and programming environment R (R Core Team, 2017).

intensification of the soil erosion. At the same time, it is likely that during rainfalls there is an increasing the proportion of sediment re-deposited within cultivated slopes and along pathways from the slopes to dry valley bottoms due to high sediment concentration in the slope runoff (Evrard et al., 2010). In contrast, any rain which falls on the unprotected tillage in the end of snowmelt period causes a high increase in erosion rate (Pabat, 1984; Øygarden, 2003).

4.2. Land cover changes

The arable land area in the three investigated catchments did not change, except for the Temeva Rechka catchment, where on the right bank of the dry valley, the low boundary of the cultivated field moved up in the interfluve direction by 10–15 m. It has undoubtedly reduced the amount of sediments entering the dry valley bottom from this slope. At the same time, the percentage of perennial grasses in crop rotations increased after 1990 at the Temeva Rechka catchment and the

Table 4
The USLE cropping coefficients (C) for 1960–1980 and 1991–2012 in the administrative regions of European Russia where the investigated small catchments are located.

Administrative regions / small catchments	C for rainfall period (May–October)		C for snowmelt period (March and/or April)	
	1960–1980	1996–2012[a]	1960–1980	1991–2012
Udmurt Republic / Kuregovo	0.24	0.19	0.60	0.57
Republic of Tatarstan / Temeva Rechka	0.34	0.30	0.75	0.76
Orenburg Oblast / Pogromka	0.40	0.31	0.89	0.81

Note. Coefficient C was almost unchanged during the period 1980–1991.
[a] Data for period 1991–1995 are not used due to the poor quality of statistical information during the first years after the USSR collapse.

Kuregovo catchment according to the information received from local farmers. The increase in perennial grasses in the crop rotation should led to reduction of soil losses during both snowmelt and rain-storm seasons. For example, according to the data of the long-term (1983–2000) monitoring on the experimental runoff plots in Lithuania, the annual erosion rate from the field under perennial grasses was less than 0.01 Mg ha^{-1}, and soil losses from the plot under winter rye and spring barley were 4–8 Mg ha^{-1} and 11–32 Mg ha^{-1}, respectively (Jankauskas et al., 2004). According to the data of the 14-year (1982–1995) monitoring of thawed runoff and soil erosion during snowmelt at some small catchments in the south of the forest zone within the Protva River basin (Kaluga Oblast, Russia), the average annual erosion rates there were 0.4–2.9 Mg ha^{-1} and 0.02–0.05 Mg ha^{-1} depending on the morphology of the catchment area within the fields under autumn fallow and perennial grasses, respectively (Golosov, 2006). It should be noted that, in both cases, according to the monitoring results, there is also a clearly declining trend in erosion rates during snowmelt due to the surface runoff reduction during the period of observation. It was not possible to collect detailed information about crop-rotation changes for 1963–2015 in the investigated catchments. However, such data in a generalized form were collected for each administrative region where the investigated catchments are located (Rosstat, 2015). The USLE cropping coefficient for rainfall period reduced since the USSR collapse in 1991 in all the areas studied (Table 4). It is likely that it also promoted some reduction in soil losses.

5. Conclusion

The significant (as a minimum by 2–3 times) decrease of soil erosion rates in the eastern part of the Russian Plain during the last 30 years was identified based on the assessment of changes in the sedimentation rates for two-time intervals (1963–1986 and 1987–2015) within the first-order agricultural catchments valley bottoms located in the different landscape zones of the study region. This contradicts the results of soil erosion rates assessment for similar time intervals for the forest-steppe and steppe zones of the Russian Plain which were based on the erosion model calculations, but it is in general agreement with the erosion model assessment for the forest zone (Golosov et al., 2017a). The contribution of crop rotation changes in reduction of soil losses is visible in the Kuregovo catchment and on the whole in the south of the forest landscape zone of the eastern part of European Russia. The lack of detailed information about crop rotations at the Temeva Rechka (the forest-steppe zone) and the Pogromka (the steppe zone) catchments for the both time intervals (1963–1986 and 1986–2015) did not allow evaluating the contribution of land cover changes to sedimentation/erosion rates. However, it is unlikely that contribution of changes in land cover has considerably reduced soil losses during last three decades, if compared to the USLE cropping coefficients changes at the regional scale for the two-time intervals. It is more likely that considerable reduction of soil erosion rates during snowmelt is a more important cause of the decline in sedimentation rates in the dry valley bottoms of all the investigated catchments. This suggestion is supported by several observations: serious reduction of gully head retreat rate during the two last decades nearby the Kuregovo catchment; results of sharp reduction of the snowmelt surface water runoff during the last 2–3 decades over the long-term monitoring at a few experimental stations located in the forest-steppe and steppe zones of the Russian Plain, and the reduction in water discharges and sediment yield during snowmelt in the regional rivers also during the last three decades. The reduction in soil losses from cultivated lands during snowmelt in the southern part of the Russian Plain is expected to lead to the following positive consequences for environment, economy and population health of the regions of European Russia: a) a reduction in land degradation, conservation of soil fertility; b) a decrease of surface water contamination by sediment and sediment-associated pollutants; c) a reduction in siltation rates in ponds, reservoirs, lakes and river channels, and, as a consequence, conservation of biodiversity in ecosystems in land waterbodies.

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